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PORTABLE, AMBIENT AIR MICROCLIMATE COOLING IN SIMULATED DESERT AND TROPIC CONDITIONS

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ABSTRACT

We examined the feasibility of providing ambient air during exercise and conditioned air during rest on reducing physiological strain and optimizing tolerance time. Six male soldiers attempted 250-min exposures in hot/dry and hot/wet environments. Subjects wore chemical protective clothing over the combat vehicle crewman uniform and an air-cooled vest. They alternated between 50 min of treadmill walking (420 W) and 50 min of rest (105 W). During the walks, a backpack mounted blower provided a total of 10 or 18 cfm of air to the vest and face; while subjects received 18 cfm of conditioned air from an umbilical during rest. A control test with conditioned air during rest, but only a ventilated facepiece during work was also conducted in the hot/dry environment. In the hot/dry environment the ambient air backpack extended ($p < 0.05$) tolerance time and significantly reduced rectal temperatures, heart rates and sweating rates compared to control; no differences were found between 10 and 18 cfm. In the hot/wet environment, tolerance time was extended compared to a predicted tolerance time assuming no microclimate cooling. We conclude that the ambient air backpack reduced physiological strain and improved tolerance time of combat vehicle crewmen during exercise in the heat. In addition, since the physiological and tolerance time responses with the 10 cfm airflow were midway between the control and 18 cfm airflow results, further tests may find an intermediate airflow rate which significantly improves performance while minimizing the backpack blower size.

Index Terms: auxiliary cooling, heat stress, chemical protective clothing.

INTRODUCTION

Personnel who work with toxic substances or in a contaminated environment must wear protective clothing. The insulation and low moisture permeability of protective clothing severely limits the body's capacity for both sensible and insensible heat exchange with the ambient environment. Therefore, if these personnel must perform physical work and/or are exposed to hot environmental conditions, they may not be able to adequately dissipate body heat to the environment. The magnitude of this heat stress problem is well documented (3,4,5,6,14). Without microclimate cooling, exposure time while performing physical work at a moderate metabolic rate in a hot environment in protective clothing may be limited to 60 minutes or less (1,2,9,13). It has become apparent that the primary approaches to extend exposure time under these conditions are by use of work/rest periods (7) and/or microclimate cooling of the individual (8,9,11).

The Individual Protection Directorate, U.S. Army Natick Research, Development and Engineering Center (USANRDEC), has developed an air-cooled vest for use by soldiers wearing nuclear, biological, chemical (NBC) protective clothing. Previous experiments which have supplied conditioned air (cool and dry) to the vest have shown it to significantly reduce thermal strain and increase tolerance time of soldiers wearing chemical protective clothing in the heat (8,9,11,13).

Numerous occupational tasks which require personnel to move freely over large areas prevent the delivery of conditioned air from a stationary air conditioner via umbilical hoses to the air-cooled vest. To alleviate the potential heat stress problem of dismounted combat vehicle crewmen, USANRDEC, has developed a portable ambient air cooling backpack, which supplies a flow of unconditioned (ambient temperature) but filtered air to the microclimate conditioning vest.

We examined the feasibility of using an ambient air microclimate vest-backpack system to reduce thermal strain of soldiers performing physical work in NBC clothing. The experiments were performed in a hot-dry (desert) condition and a hot-wet (tropic) condition which would primarily require insensible and sensible heat exchange with the environment, respectively. Although these environments required different avenues of heat exchange, their magnitude of thermal burden should be similar as they have similar WBGT values of 27.8°C and 28.2°C for the hot/dry and hot/wet environments, respectively.

METHODS

Six male soldiers volunteered to participate in the study. They received a physical examination and were informed of the purpose and procedures of the study, any known risks and their right to terminate participation at will without penalty. Each expressed understanding by signing a statement of informed consent. The physical characteristics of the subjects were ($\bar{X} \pm$ SD): age, 21 ± 2 years; height, 178 ± 8 cm; weight, 75.8 ± 4.2 kg; and body surface area, 1.9 ± 0.1 m^2.

Testing was conducted in June in Natick, MA. All six subjects had previous experience wearing the chemical protective clothing. Prior to any experimental testing, the subjects were heat acclimated by walking on a level treadmill at $1.34\ m \cdot s^{-1}$, $3\ h \cdot d^{-1}$, in a 35°C T_{db}, 30°C T_{dp} environment. During the heat acclimation, they wore shorts, T-shirts, socks and running shoes. The heat acclimation program was discontinued after four days since the subjects did not decrease their final exercise heart rate and rectal temperature responses between days 3 and 4. .

Following heat acclimation, the subjects attempted four separate 250-min heat exposures while wearing the USANRDEC Microclimate Conditioning Vest

(MCV)-backpack system, combat vehicle crewman uniforms (including body armor) and chemical protective clothing (overgarment, overboots, M25 CB mask/hood, gloves). This clothing ensemble had a clo value of 1.75 in still air. Environmental conditions were either 35.1°C T_{db} and 19.7°C T_{dp} or 40.6°C T_{db} and 1.0°C T_{dp} (see Table 1) with an air velocity of 1.1 $m \cdot s^{-1}$. During these tests, the subjects alternated between 50 min of treadmill exercise (metabolic rate ~420 W) and 50-min of seated rest (metabolic rate ~105 W). The treadmill exercise was performed at 1.1 $m \cdot s^{-1}$ and 0% grade. During the exercise period, the subjects connected their MCV system to the ambient air backpack. The total flow rate provided by the backpack was either 10 or 18 cfm (see Description of Microclimate System). During the seated rest periods, conditioned air was supplied to the MCV at 22.2°C T_{db}, 15.0°C T_{dp} at 18 cfm. It was anticipated that rest periods with conditioned air cooling would enable the subjects to dissipate the heat storage that occurred during the exercise bouts. The environmental conditions and presentation order are outlined in Table 1.

During a practice day (comfortable environment, 22°C), expired air samples were collected in Douglas bags; volume and oxygen and carbon dioxide concentrations were measured and oxygen uptake was calculated. These measurements were obtained with the subjects dressed in the chemical protective clothing and wearing the MCV-backpack system since a previous study (12) observed that adding layers of clothing and a backpack load increases the metabolic rate. During all tests, the electrocardiogram was obtained from chest electrodes (CM5 placement) and displayed on an oscilloscope-cardiotachometer unit. Rectal temperature was recorded from a thermistor probe inserted approximately 10 cm beyond the anal sphincter. Rectal temperature was printed and plotted every two minutes using a computer-controlled data acquisition system. Total body sweating rate was determined from pre- and post-test nude body weights, adjusted for water intake and urine output. Subjects were encouraged to drink water throughout the exposures. Water was ingested through a flexible plastic "straw" threaded under the subject's hood and mask.

The test was terminated for any subject: whose rectal temperature reached 39.5°C, whose heart rate exceeded 180 b • min^{-1} for five minutes continuously, who voluntarily withdrew, or who was removed at the discretion of the medical monitor or principal investigator.

A one-way repeated measures analysis of variance was used to compare endurance times and sweating rates among the four experimental tests. Rectal temperature and heart rate data were analyzed using a two-way (cooling combination by time) repeated measures analysis of variance. Significance was accepted at the $P < 0.05$ level.

Description of microclimate system. The USANRDEC vest is designed to provide chest, neck and back cooling via a hose and manifold system mounted on an open weave fabric. The air is distributed through the chest and back manifolds and holes in the hoses at a ratio of approximately 40% to the chest, 20% to the neck and 40% to the back. The ventilated facepiece (M25 CB mask) can be used without the vest. The inlet air flow is split by an air connector into 6.5 cfm to the vest and 3.5 cfm to the facepiece at 10 cfm, and 14.5 cfm to the vest and 3.5 cfm to the facepiece at 18 cfm. The air exits diffusely, primarily at the waist. The vest is worn over the undershirt and under the body armor and weighs 0.45 kg. The ambient air backpack provides a flow (10-18 cfm) of filtered air at ambient temperature for circulating through the vest and facepiece. The backpack is constructed of a fiberglass reinforced ABS molded plastic frame, NBC filter/ABS plastic housing and motor blower (Fig. 1). It is powered by rechargeable nickel-cadium battery packs and weighs 5 kg.

The maximal theoretical cooling capacities of the vest when supplied with the different air combinations are shown in Table 1. The theorectical maximal dry convective cooling capacity was calculated as the product of flow rate, air density and specific heat of air, and the gradient between inlet air temperature and an assumed skin temperature of 35°C. The theoretical maximal evaporative cooling capacity was calculated as the product of flow rate, latent heat of evaporation of water at 35°C, and gradient between moisture content of inlet air and air saturated at an assumed skin temperature of 35°C.

RESULTS

Hot-Dry Environment. Table 2 provides the number of subjects completing each exercise and rest period. During the control condition A; (no cooling during exercise), only three subjects completed the third exercise bout. For the 10 and 18 cfm conditions, four and six subjects completed the third exercise bout respectively. Fig. 2 indicates that this translated into tolerance times of 176, 209 and 250 min for the control, 10 and 18 cfm conditions, respectively. Condition C was significantly different ($p < 0.05$) from condition A.

Fig. 3 presents the mean rectal temperature (T_{re}) responses during the three test conditions in the hot/dry environment. Considerable heat storage occurred during each exercise bout for all three conditions, however, during the rest periods the conditioned air was effective in dissipating body heat. Although there was a gradual increase in peak T_{re} values with each exercise bout, it was small (~0.2°C) and not significant.

Due to subject attrition, statistical analysis of the peak T_{re} response was made only for the first exercise bout. During the first exercise bout, the T_{re} values during the 10 and 18 cfm test conditions were significantly lower ($p < 0.05$) than the control condition. Furthermore, the ΔT_{re} during the control test

($1.28 \pm 0.31°C$) was much greater ($p < 0.05$) than the 10 cfm ($0.72 \pm 0.26°C$) and 18 cfm ($0.71 \pm 0.31°C$) test conditions. Total body sweating rate (Fig. 4) was reduced during the 10 cfm condition by 10% and the 18 cfm condition by 17% ($p < 0.05$) in comparison to the control. Fig. 5 presents the final exercise heart rate responses for each exercise bout. During the first exercise bout, use of the ambient air backpack (conditions B and C) elicited significantly ($p<0.05$) lower heart rate responses than the control test.

Warm-Wet Environment. In the warm-wet environment, no control test was conducted. Consequently, no comparison can be made regarding the effectiveness of the MCV-backpack system in reducing physiological strain. However, it is possible to compare the effectiveness of the 10 cfm versus 18 cfm MCV-backpack combination. For the 10 and 18 cfm test conditions, four and six subjects completed the third exercise bout, respectively. Fig. 2 demonstrates that despite this subject attrition, no significant differences were found for tolerance time. Rectal temperature response showed the same relationship over time as during the hot-dry environment. During exercise, the individuals stored body heat which was dissipated by the conditioned air during the rest periods. The ΔT_{re} during the first exercise bout was 1.19 ± 0.20 and 1.26 ± 0.25 for the 10 and 18 cfm conditions, respectively. No differences were found in T_{re} between conditions D and E. There were also, no significant differences in total body sweating rate (Fig. 4) or heart rate responses between the two conditions.

DISCUSSION

We examined the feasibility of ambient air microclimate cooling for individuals performing physical work in desert and tropic environments. Two environments were selected that require different avenues of heat dissipation, but should elicit similar physiological strain since the WBGT indices were the same. Due to limited environmental chamber and human test subject availability, we were only able to complete a control experiment in the hot-dry environment. However, given that the two environments had similar WBGT indexes, tolerance time might be expected to be similar in the hot-wet condition. Based on our computer model of physiological strain during exercise-heat stress, the predicted (7) tolerance times with no microclimate cooling were 150 and 140 min for the hot-dry and hot-wet environments, respectively. Therefore, the ambient air cooling back pack was successful in reducing physiological strain and extended tolerance time in both environments.

In the hot-dry environment, the 18 cfm condition had a slight advantage over the 10 cfm condition for extending tolerance time but no discernable differences were noted for T_{re}, heart rate or sweating rate responses. The theoretical maximal cooling capacities of the MCV-backpack were 236 and 528W at the 10 and 18 cfm air flow rates respectively. These values assume a fully wetted skin under the vest and saturation of the outlet air. Since our ambient air temperature of 41°C was probably greater than skin temperature, the heat dissipation would be expected to occur via evaporation. With mean total body sweating rates of 864 and 798 $g \cdot h^{-1}$ potential evaporative cooling was 582 and 537 W for B and C tests, respectively. However, the body heat storage during the exercise bouts indicates that all of the secreted sweat was not evaporated. This indicates that the skin was not fully wetted under the vest, or more probably that sweating occurred at body regions not ventilated by the vest so that evaporative cooling did not occur. Compared to the control test, the average total body sweating rates in the hot/dry environment were reduced by 89 and 124 $g \cdot m^{-2} \cdot h^{-1}$ with the 10 and 18 cfm MCV-backpack, respectively. Although these water savings may appear small, a recent study (unpublished) conducted at our Institute, observed nearly a 40 percent decrease in ad libitum water consumption during walking while wearing a M17A2 chemical protective mask equipped with a drinking tube. Therefore, microclimate cooling will help avoid dehydration which even at moderate levels will cause increased exercise heat storage (10). Additionally, logistic constraints may limit the supply of available drinking water. Finally, it should be stated that the use of ambient air systems in extreme hot-dry conditions can pose a problem by irritating the skin (11).

In the hot-wet environment, the 18 cfm condition had over a two-fold greater theoretical cooling capacity than the 10 cfm condition, however, no clear differences were found for tolerance time and physiological strain even though all the subjects did complete the exposure with the vest supplied with 18 compared to 10 cfm of air. Both flow rate conditions would primarily employ sensible heat exchange to dissipate body heat during the exercise bouts in this environment. Although the 18 cfm condition provided an additional 8 cfm of flow to the vest, this additional air flow may not be distributed over an increased skin area and thus not provide efficient heat dissipation. Furthermore, considering the small gradient between the body core and the ambient air temperature (~3°C), effective convective heat loss would require fairly large air flows over the available skin area. Unfortunately, we could not monitor outlet temperature from the vest to determine the actual efficiency. Since delivery of air at 18 cfm did not significantly improve tolerance time or reduce physiological strain compared to the 10 cfm backpack, the results suggest that a smaller blower intermediate between 10 and 18 cfm output may be sufficient to provide ambient air cooling to the user. The use of a smaller blower can result in a lower backpack weight and/or longer battery life.

During the rest periods, the MCV was ventilated with conditioned air at 18 cfm. The temperature of the conditioned air was 18 and 13°C lower than ambient temperatures of the hot/dry and hot/wet environments, respectively. Generally 10 to 15 min into the rest period the subjects complained of their trunk feeling chilled. It is likely that the MCV's combined convective and evaporative cooling capacity was excessive given the low metabolic rate during the rest period. During the rest period, T_{re} tended to drop rapidly for approximately 30 min. Then the rate of decline in T_{re} slowed. For all subjects, the lowest T_{re} attained during the rest periods was always higher than initial temperature. The cool, dry air provided during the rest period may have reduced the effective surface area available for evaporative cooling by shutting off sweat glands. More efficient body cooling may be possible if the subjects controlled the air flow rate or temperature of the conditioned air to the vest.

The primary strategies for extending physical work time in the heat are by use of work-rest cycles (7) and/or microclimate cooling (8,9,11). Depending upon the operational requirements, work intensity and environmental conditions, the work-rest cycles may have limited military usefulness. Microclimate cooling likewise has limitations. It is difficult to provide conditioned air to dismounted individuals, ambient air systems cooling capacity is dependent upon the ambient environment, liquid systems can impose a large weight penalty on the wearer and tethered systems limit the user's freedom of movement. The present investigation attempted to combine both strategies to solve the exercise-heat stress problem. Our data indicate that this combined strategy of work periods with an ambient air cooling backpack and rest periods with conditioned air cooling has good potential for extending tolerance time and reducing strain.

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FIGURE LEGENDS

Fig. 1. Ambient Air Backpack.

Fig. 2. Tolerance times ($\bar{X}$, SD) for MCV-backpack in hot/dry environment: (A) control, (B) 10 cfm, (C) 18 cfm; and in warm/wet environment: (D) 10 cfm, (E) 18 cfm. * indicates $p<0.05$.

Fig. 3. Mean peak rectal temperatures plotted across time for (A) control, (B) 10 cfm, (C) 18 cfm MCV-backpack tests, hot-dry environment. * indicates $p<0.05$.

Fig. 4. Sweating rates ($\bar{X}$, SD) for MCV-backpack in hot/dry environment: (A) control, (B) 10 cfm, (C) 18 cfm; and in warm/wet environment: (D) 10 cfm, (E) 18 cfm. * indicates $p<0.05$.

Fig. 5. Heart rates ($\bar{X}$, SD) at end of exercise periods for: (A) control, (B) 10 cfm and (C) 18 cfm MCV-backpack tests. * indicates $p<0.05$.

TABLE 1. TEST CONDITIONS.

Condition	Test Day	Ambient Dry Bulb (°C)	Ambient Dew Point (°C)	Airflow (CFM)	Maximal Evaporative (W)	Maximal Convective (W)	Total Cooling (W)
A	5	40.6	1.0	-	-	-	-
B	4	40.6	1.0	10	256	-20	236
C	3	40.6	1.0	18	571	-43	528
D	2	35.1	19.7	10	173	0	173
E	1	35.1	19.7	18	387	0	387
* Rest	-	22.2	15.0	18	475	106	581

*Conditioned Air provided by umbilical to vest during rest periods.

TABLE 2. NUMBER OF SUBJECTS COMPLE[illegible] EACH WORK/REST PERIOD.

Condition	Exercise 1	Rest 1	Exercise 2	Rest 2	Exercise 3
A	6	5	3	3	3
B	6	6	5	5	4
C	6	6	6	6	6
*D	5	5	4	4	4
E	6	6	6	6	6

*Note: only 5 subjects started

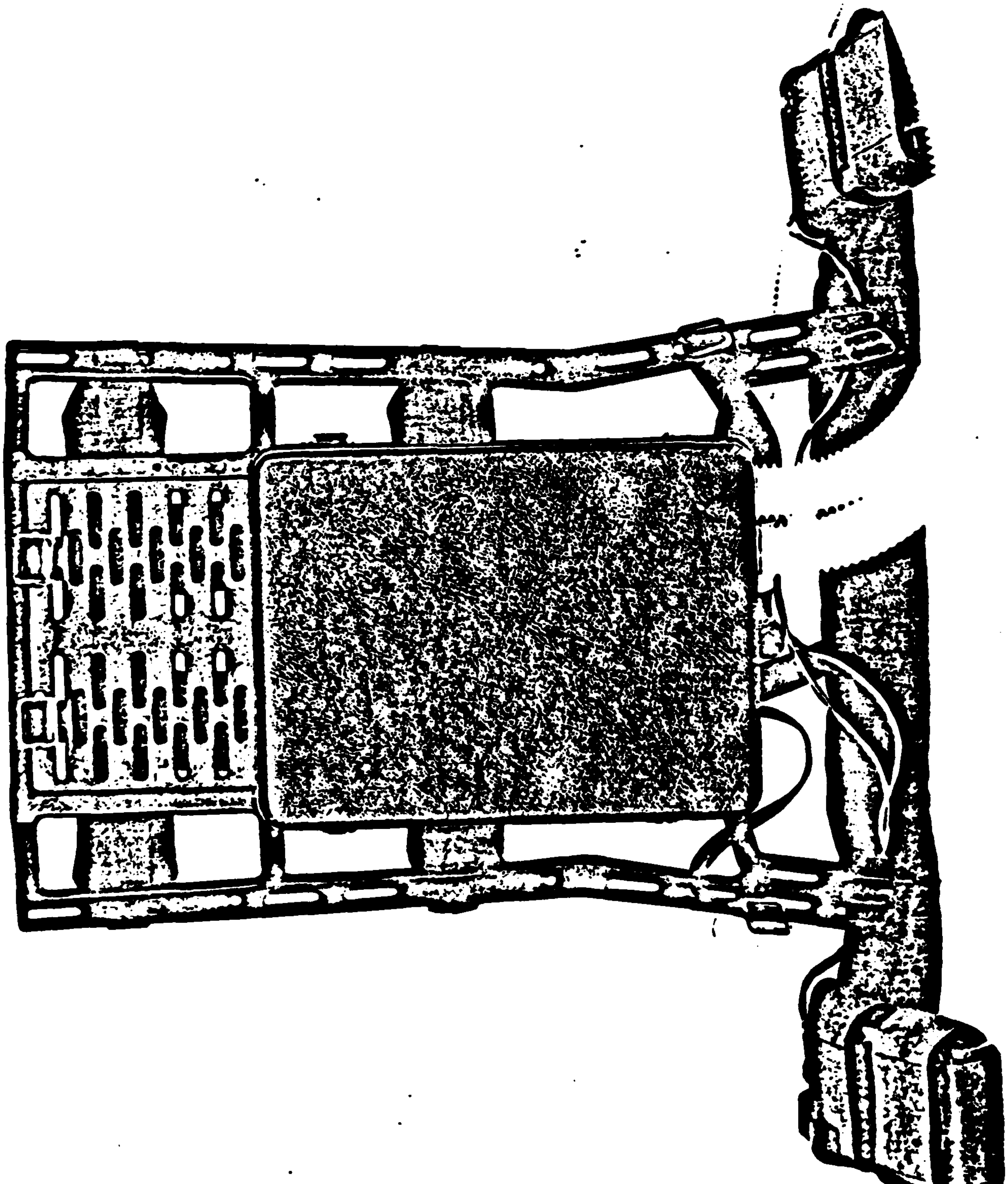
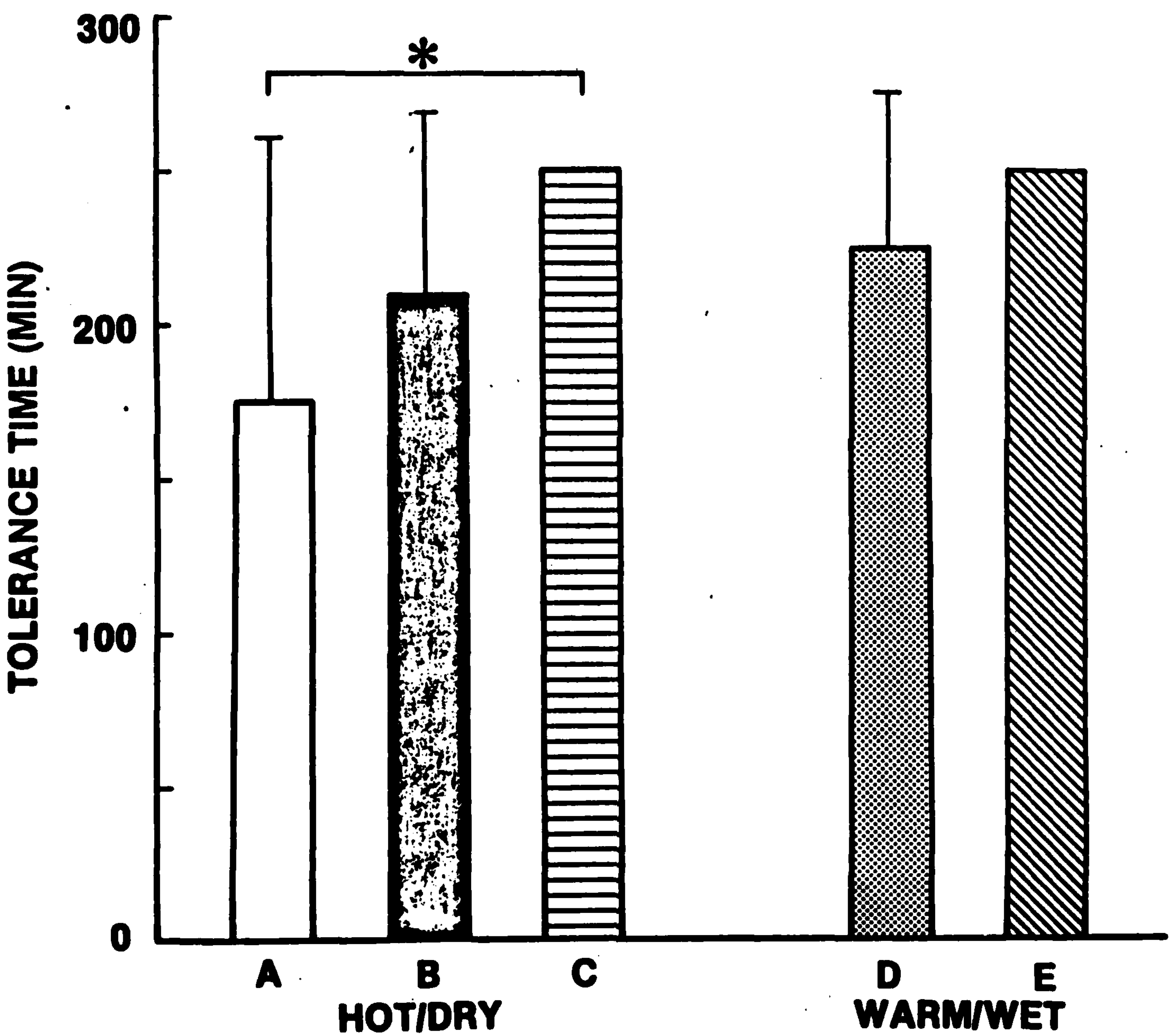
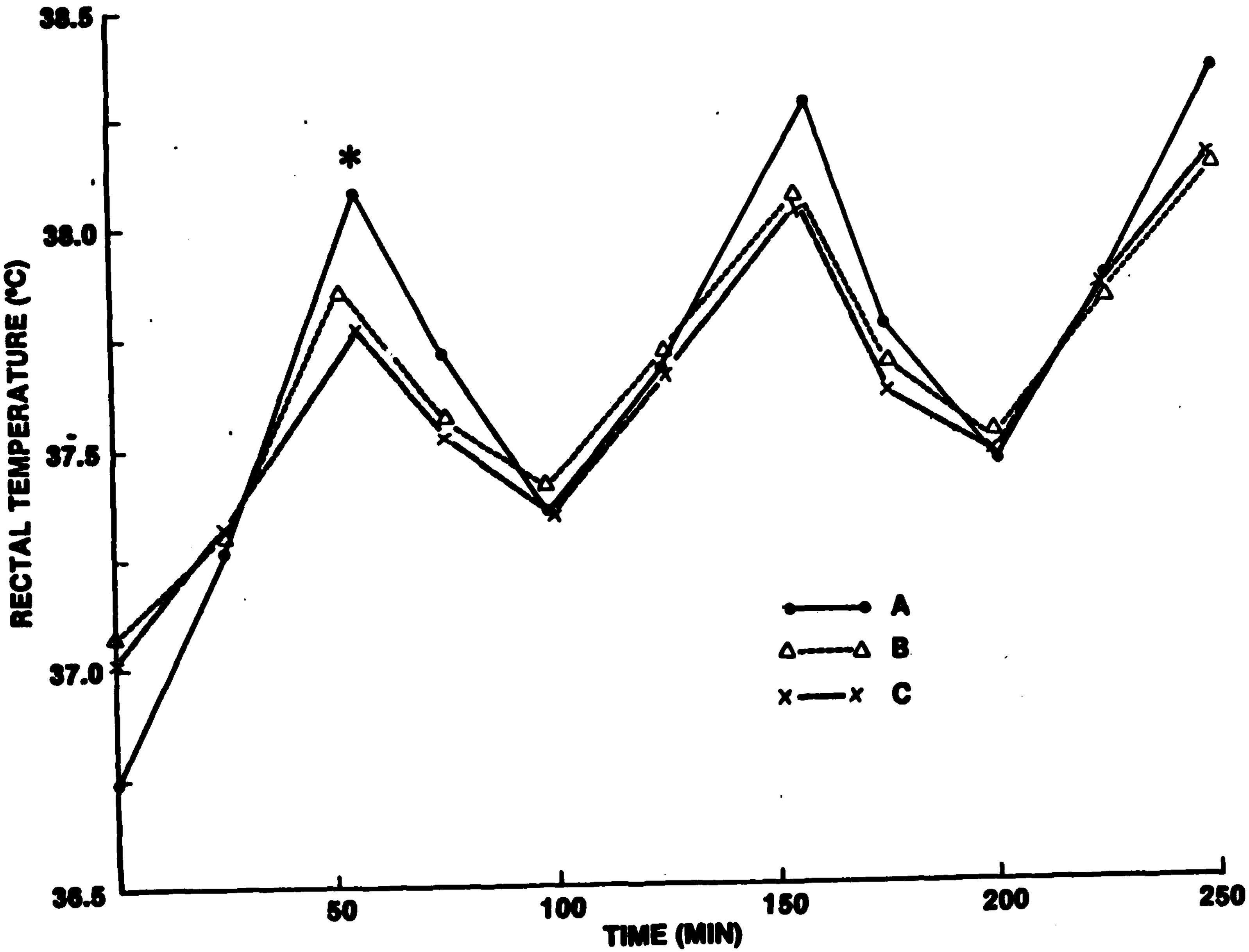
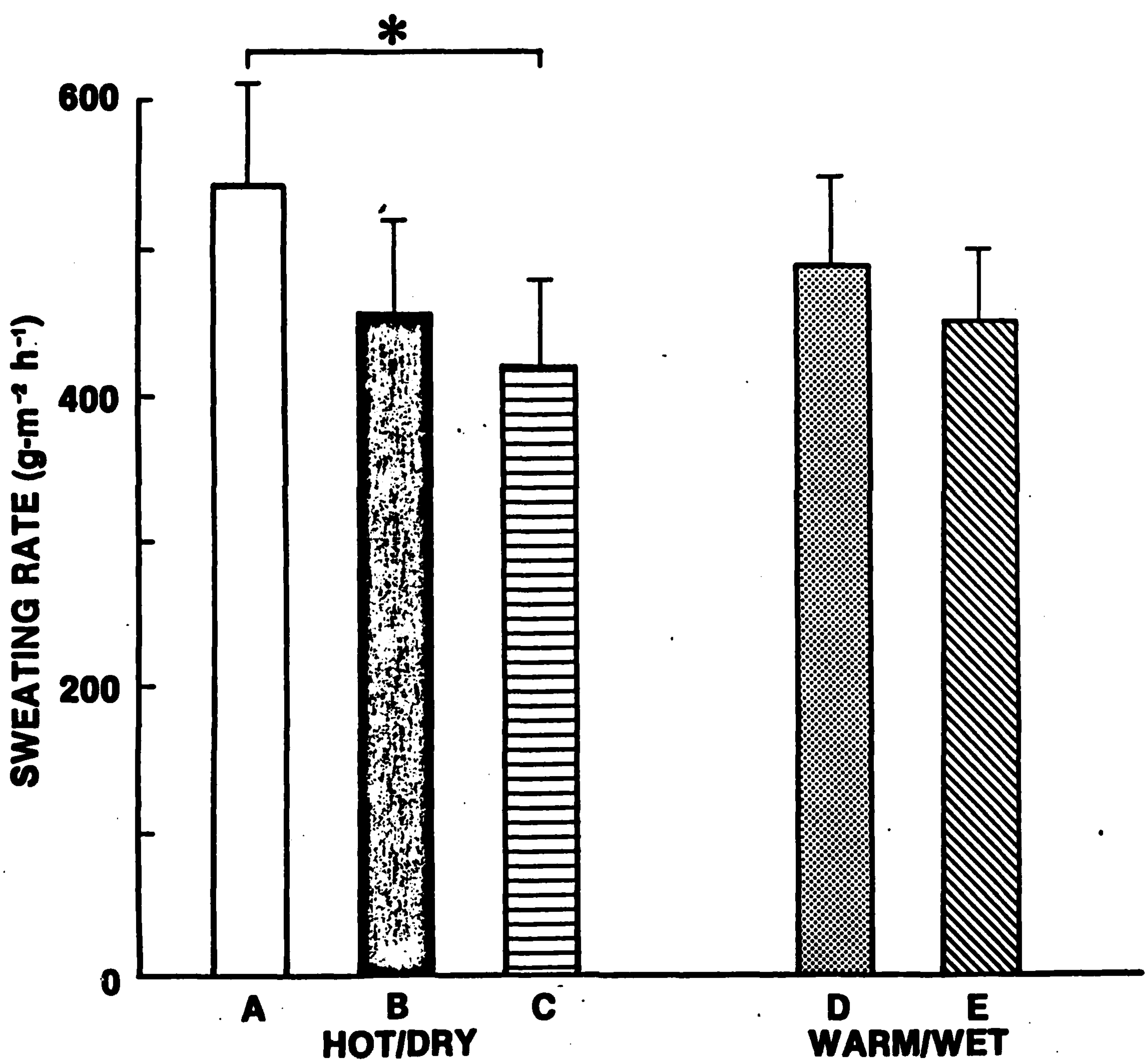


Fig 6


TOLERANCE TIME (MIN)
300
200
100
0
*
A
B
C
HOT/DRY
D
E
WARM/WET



38.5
38.0
37.5
37.0
36.5
RECTAL TEMPERATURE (°C)
*
A
B
C
50
100
150
200
250
TIME (MIN)


*
600
400
200
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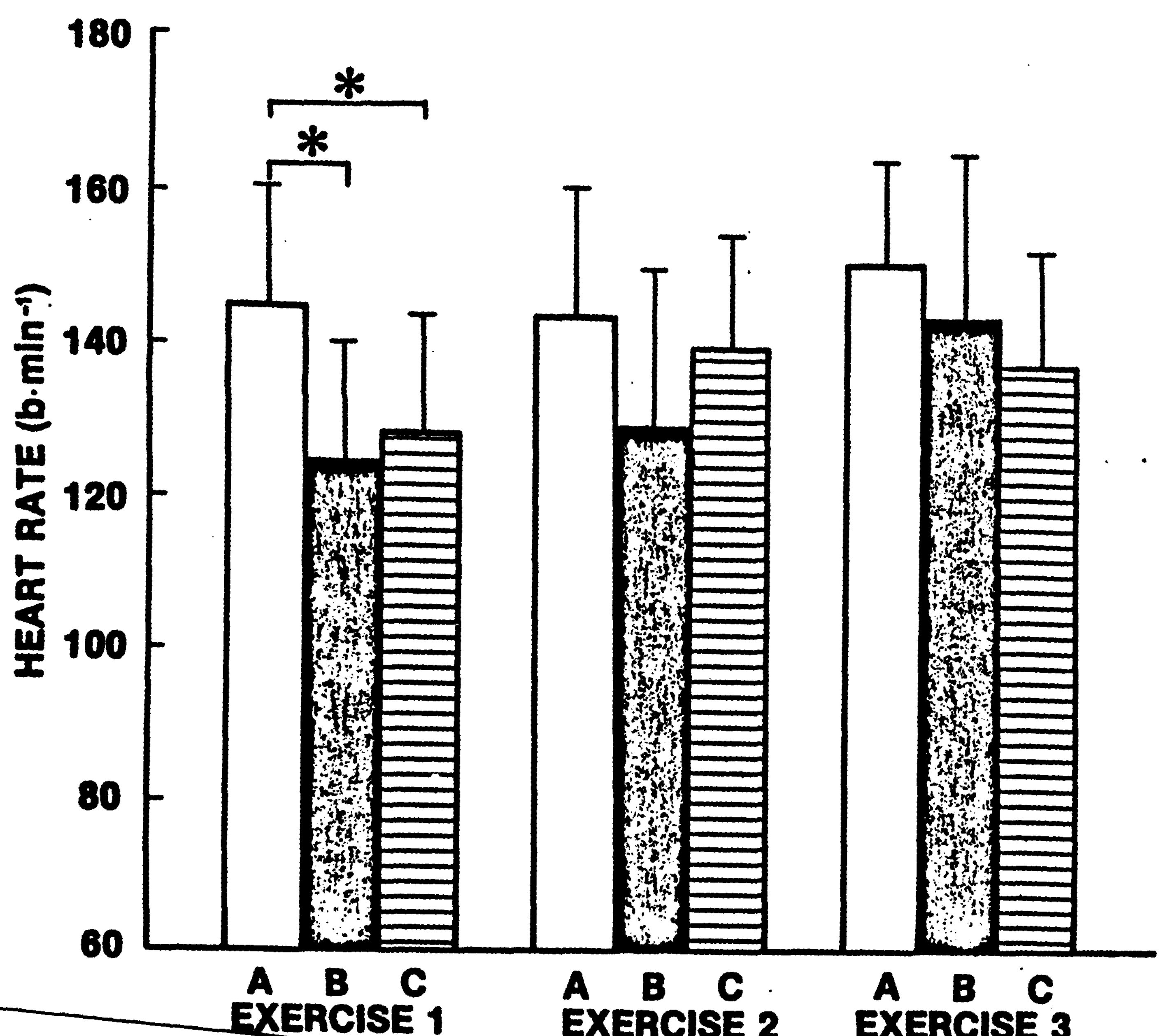
SWEATING RATE (g·m⁻² h⁻¹)
A
B
C
HOT/DRY
D
E
WARM/WET



HEART RATE (b·min⁻¹)
180
160
140
120
100
80
60
*
*
A B C
EXERCISE 1
A B C
EXERCISE 2
A B C
EXERCISE 3